Studies of rare production and decay processes of the Higgs boson at the ATLAS experiment

Proklova N.
on behalf of the ATLAS Collaboration

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ATLAS EXPERIMENT

Nikhef

Radboud University

IN·DEI·NOMINE·FELICITER

MEPhI
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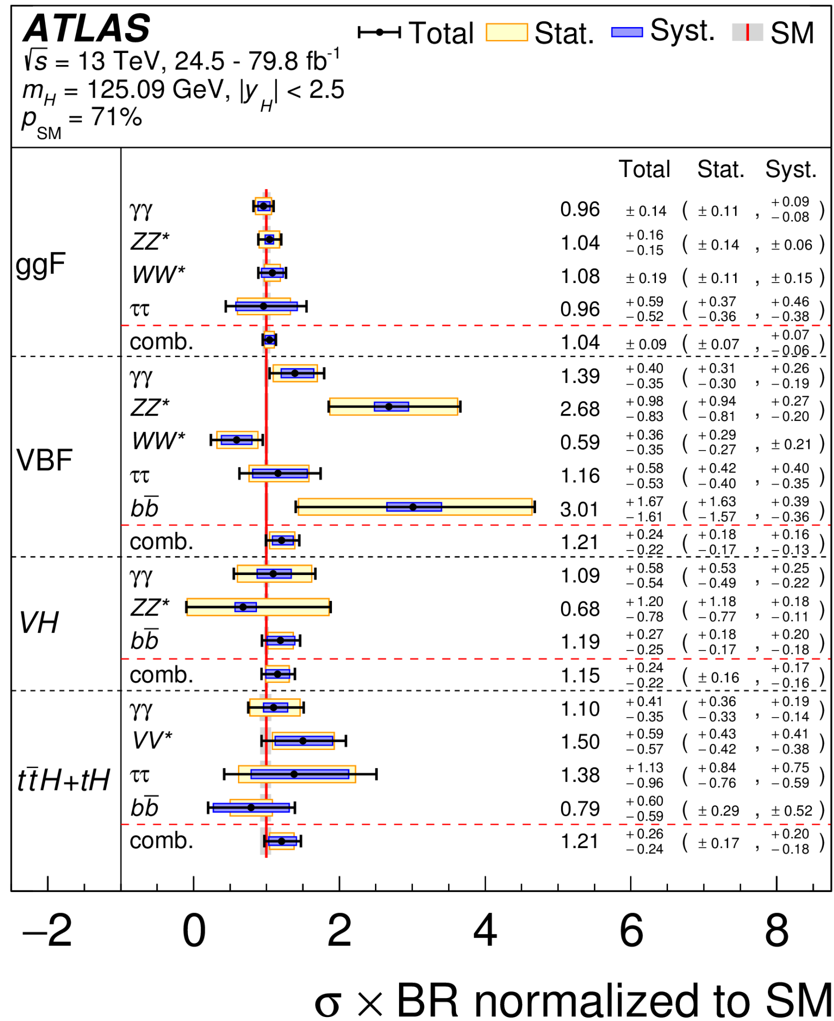
Introduction

Many Higgs boson decay channels/ production modes have been discovered and measured → **consistent** with the SM within uncertainties

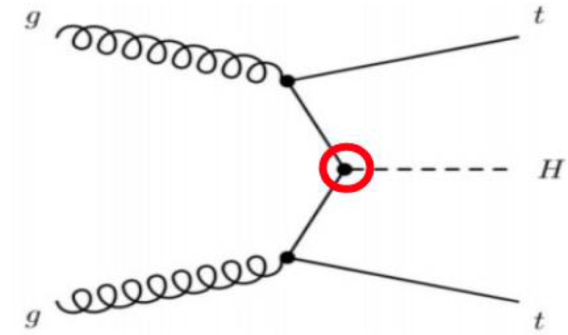


- **BUT**: BSM physics may still manifest itself in the Higgs sector.
- Rare or forbidden decays provide novel probes to new physics

- **Rare decays**: searches of H→Zγ, H→ee and H→μμ,
  CP properties probe with ttH+tH, H→γγ
- **Forbidden decays**: vanishing in the SM,
  e.g. flavour violating decays H→eτ/μτ, H→eμ

arXiv:2004.04545

ttH+tH, H→γγ – CP properties

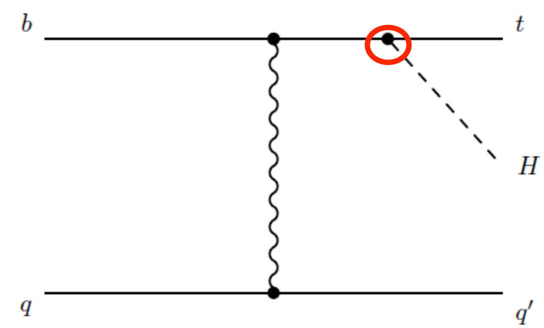


SM Higgs boson is CP-even: $J^{CP} = 0^{++}$

But ttH&tH processes allow to probe CP-violation in the top-Yukawa coupling at tree level:

$$\mathcal{L} = -\frac{m_t}{v}(\bar{\psi}_t \kappa_t \,(\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5)\,\psi_t)H$$

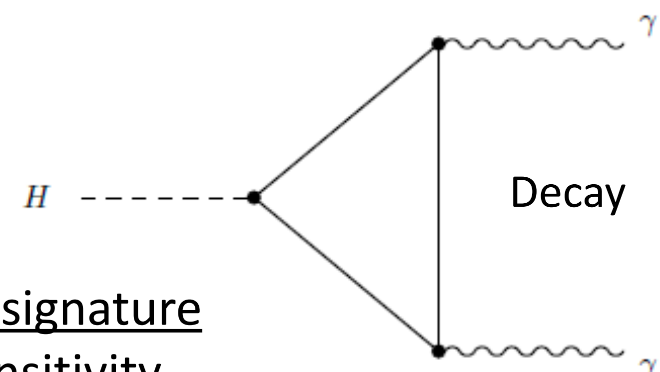
Production



Parameters of Interest:
κ_t: top-Yukawa coup.par.
α: CP-mixing angle

SM: $\kappa_t = 1$, $\alpha = 0$
CP-odd: $\alpha = 90^o$

CP-odd component can have effect on cross sections and kinematics of ttH/tH



Decay

H→γγ has clean signature and excellent sensitivity

ttH+tH, H→γγ CP: Analysis strategy

Data : full Run 2 , 139 fb^{-1}

Event selection:

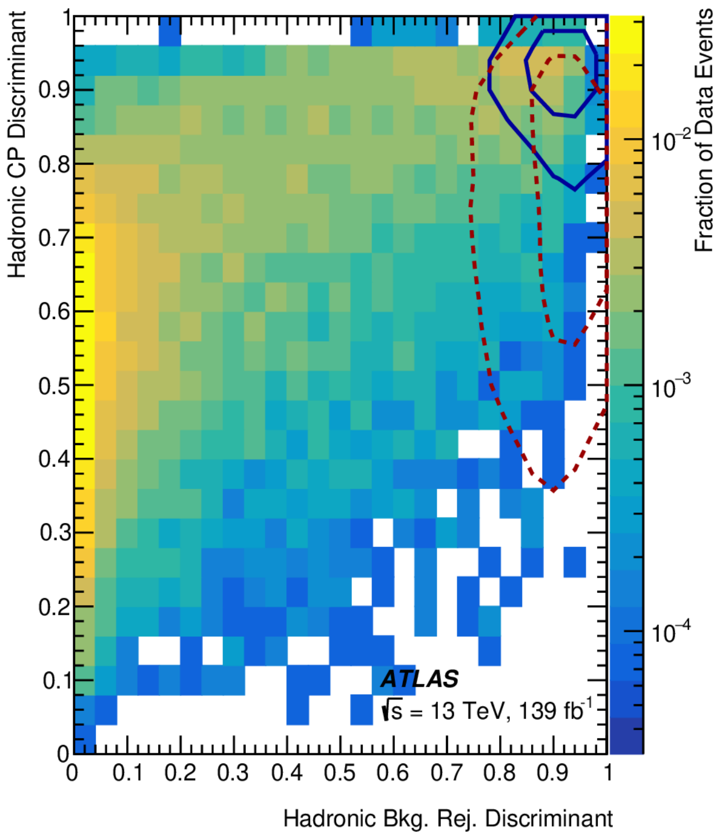
- 2 tight, isolated photons, ≥ 1 b-tagged jet
- Two regions:
  - Hadronic: N_{jets} ≥ 3, N_{lep} =0
  - Leptonic: N_{lep} ≥ 1

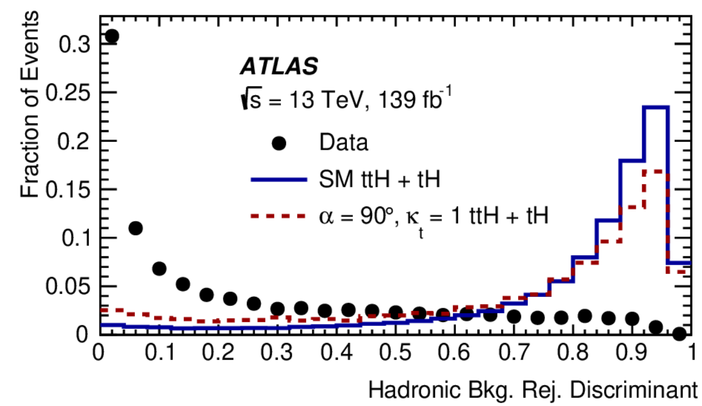
Categorisation:

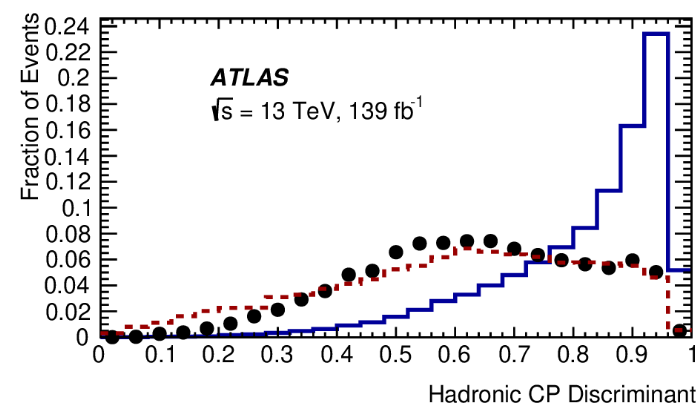
1) **Bkg. rejection BDT** to separate ttH like events from continuum bkg (non tight isolated data)
2) **CP BDT** – separate CP-even ttH/tH from CP-odd
   - 20 kinematic / angular / event variables + dedicated BDT to reconstruct top quarks
3) Event Categorisation (20 categories) based on 2D plane of BKG and CP BDTs

Signal extraction:

Simultaneous fit in all 20 categories to mγγ distribution







ttH+tH, H→γγ CP: Results

NEW

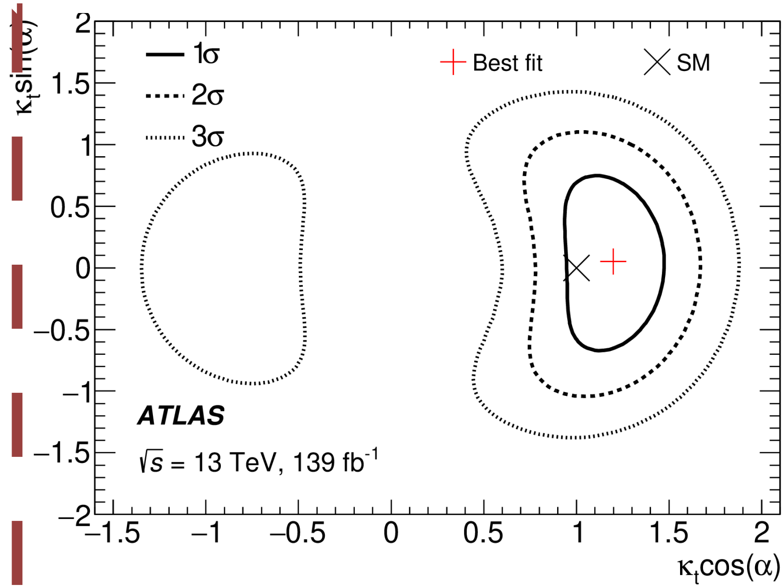
ttH significance:

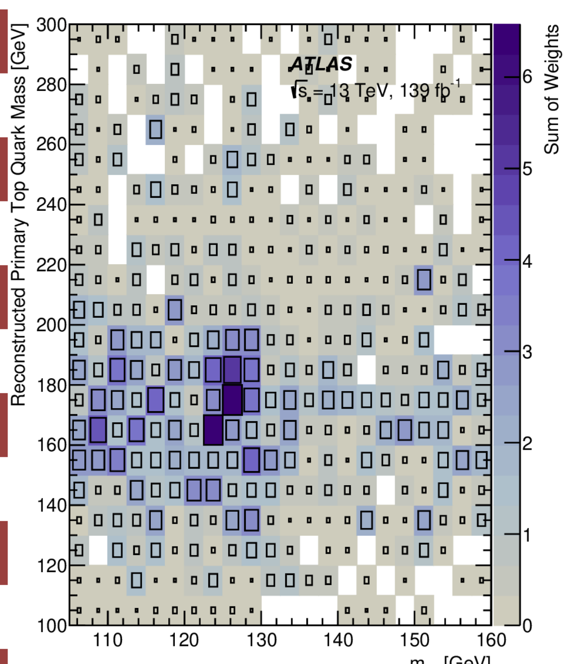
signal strength: 1.4 ±0.4(stat)±0.2(sys)

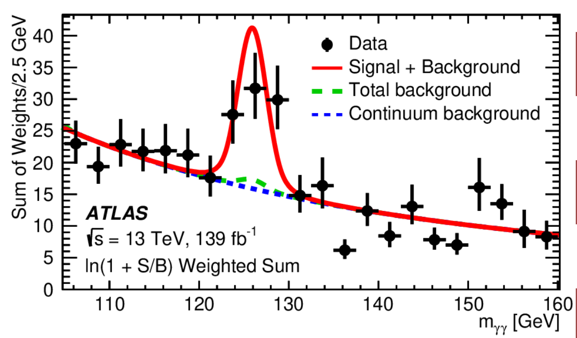
obs. (exp.) sign.: 5.2σ (4.4σ)

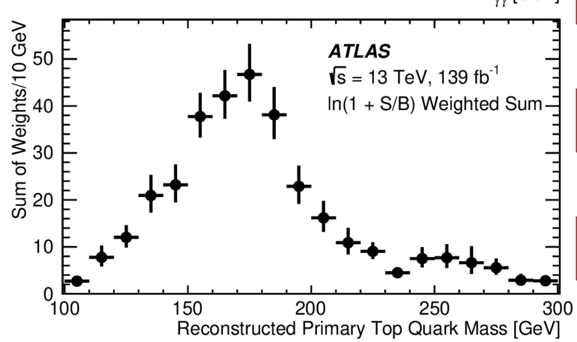
tH cross section upper limit:

obs. : < 12 x SM at 95% CL









H→γγ (and ggH) rates constrained to combination results

|α| > 43° excluded at the 95% CL (expected exclusion: **|α| > 63°**)

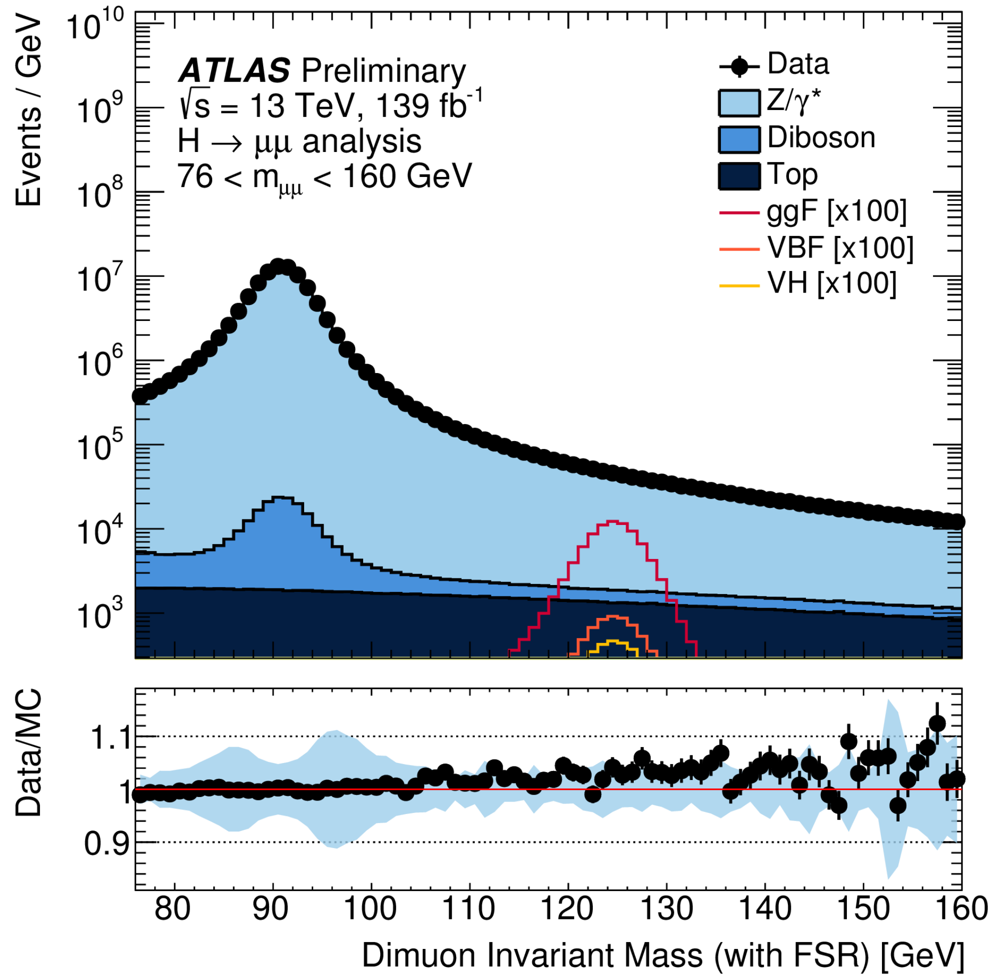
CP-odd hypothesis rejected: at **3.9σ** (expected : **2.5σ**)

H→μμ decay search

H→μμ is a sensitive channel to explore the Higgs boson coupling to the second generation of fermions

BUT: $BR_{SM}=2.2\times10^{-4}$ and large background

- Experimentally **clean & good mass resolution**
- Signal would appear as a peak in $m_{\mu\mu}$ on top of smoothly falling distribution that mainly consists of Drell-Yan process



In a $110 < m_{\mu\mu} < 160$ GeV window:
~2.5M events in data (139 fb^{-1})
mostly from Drell-Yan ($Z/\gamma^* \rightarrow \mu\mu$)
- Expected S~860 events (ε=60%)

H→μμ decay search

Analysis strategy

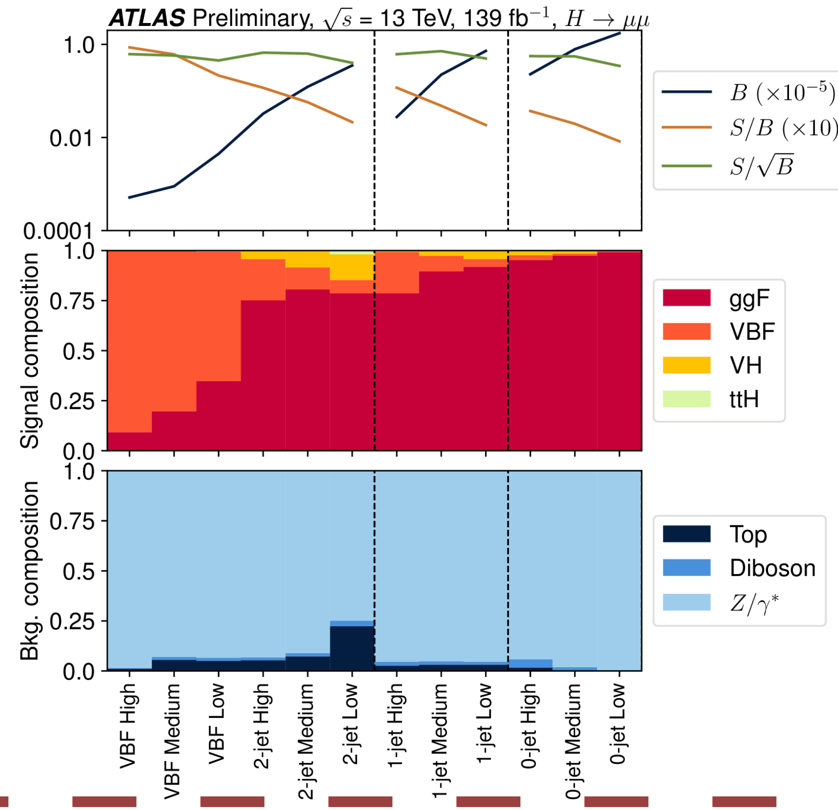
-BDT-based categorization to increase signal sensitivity (based on the **production mode**)

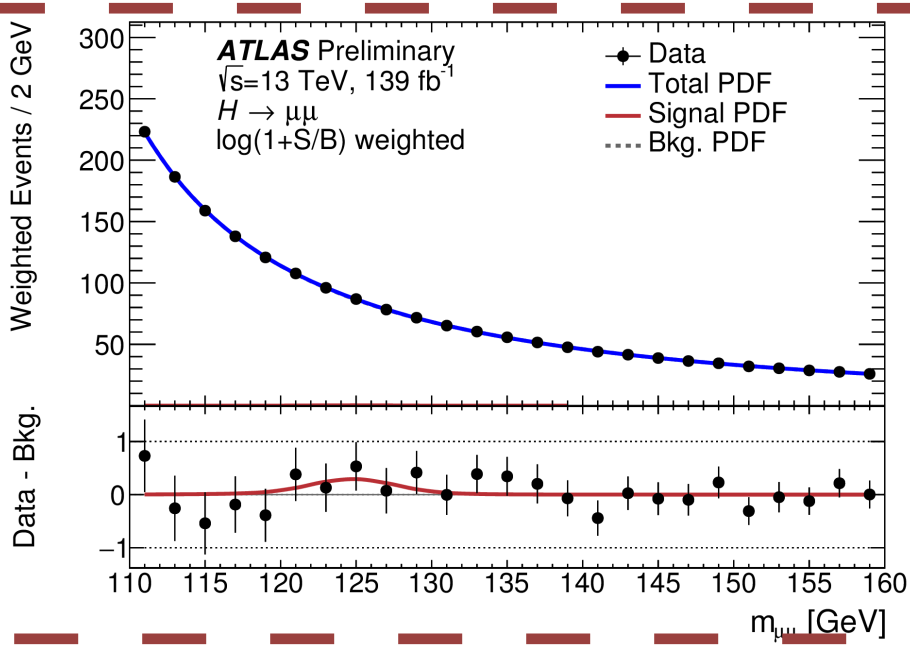
- Data driven approach used for bkg estimation

  Spurious signal (SS) estimated with large statistics fast-Sim (~700 times the data luminosity)

- S+B PDF used to fit the observed $m_{\mu\mu}$ spectra simultaneously in all the categories to derive the final signal strength μ

  Signal and bkg modelled by analytic functions





Results

No significant excess:

0.8σ obs (1.5σ exp)

μ = 0.5±0.7 (1.0±0.7 exp.) ->

μ < 1.7 @95% CL (2.2 exp)

Statistically limited

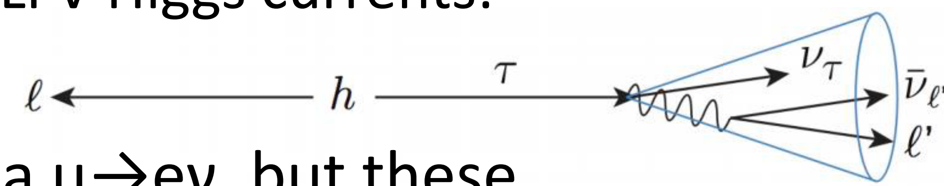
LFV with H→eτ/H→μτ/H→eμ and H→ee

Lepton-Flavour Violating decays

Neutrinos oscillations indicate that the **LFV** exists → lepton flavour **is not an exact symmetry** → Possibility for BSM physics

Many theoretical models allow the LFV Higgs currents:

H→eτ/H→μτ: $BR(H\to\tau l)\leq O(1\%)$

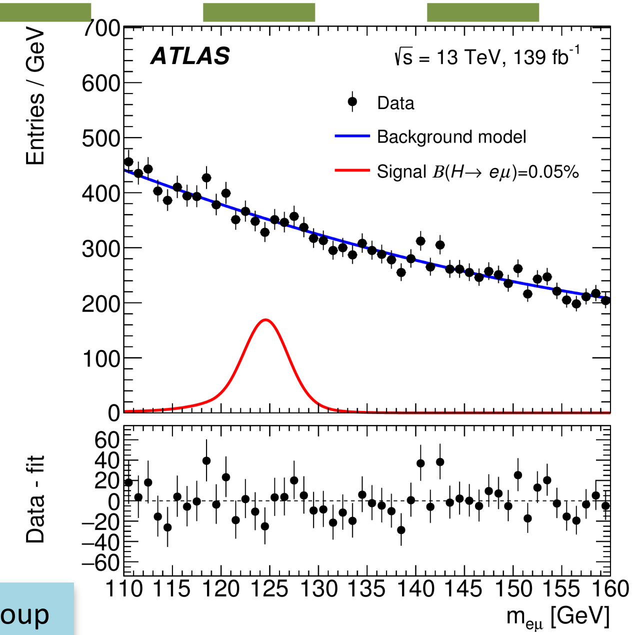


H→eμ: Indirect constraints set via μ→eγ, but these constraints rely on SM assumptions for Y_{ee} and $Y_{\mu\mu}$

BF(H→ee) is below sensitivity of the LHC due to very small Y_{ee} and large background

BUT: LHC is still most sensitive way to set constraints on this coupling

Very similar to H→μμ search, with similar signal efficiencies and backgrounds



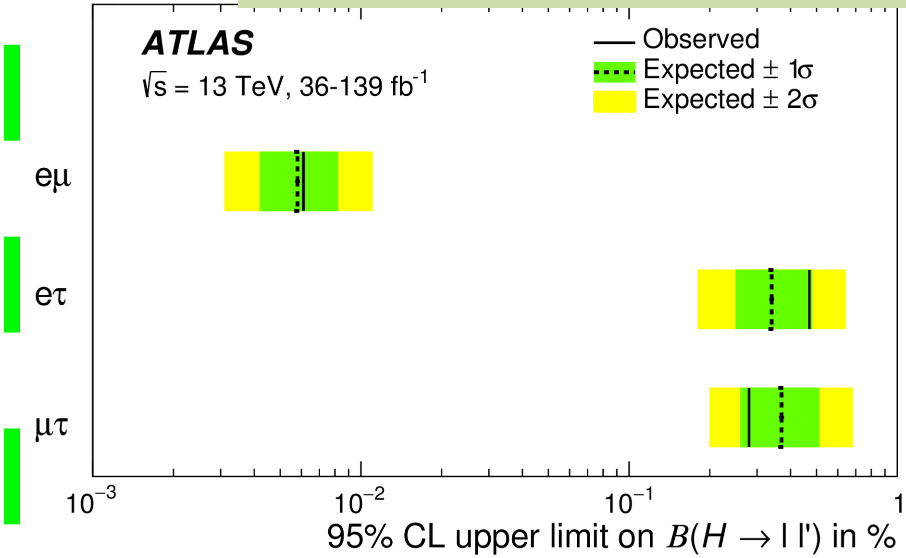
arXiv:1907.06131 arXiv:1909.10235

H→ee/H→eμ results provided by the same group

LFV with H→eτ/H→μτ/H→eμ and H→ee

No significant signal observed for any decay

Summary of ATLAS searches for Higgs LFV decays:



H→eτ/H→μτ:

BR consistent with 0 within 1σ

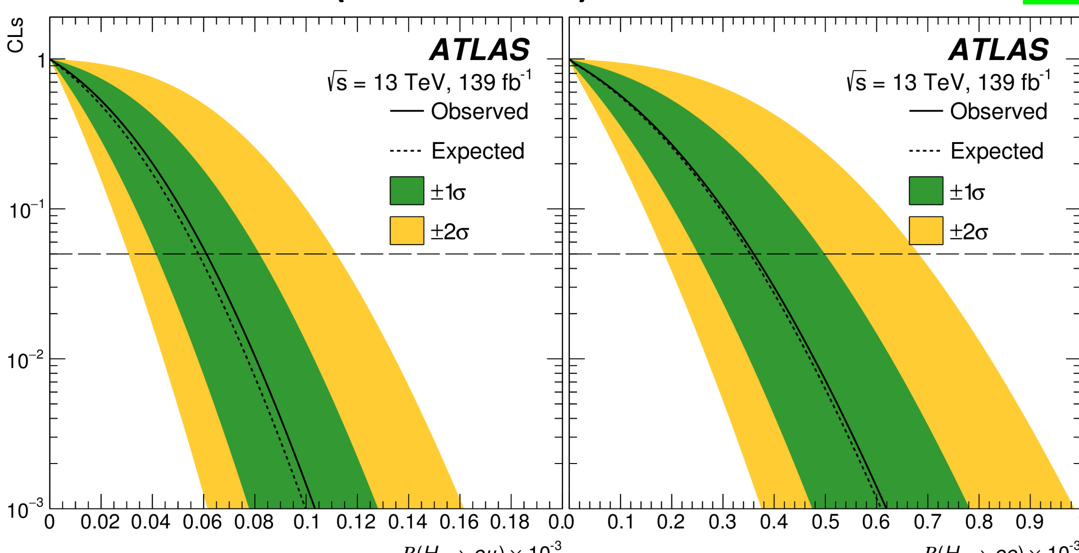
- BR(H → eτ) < 0.47% (0.34% expected)
- BR(H → μτ) < 0.28% (0.37% expected)

H→eμ:

- $B(H \to e\mu) = (0.4 \pm 2.9) \times 10^{-5}$

95 % CLS limits for obs. (exp.):

- 6.2×10^{-5} (5.9×10^{-5})



H→ee:

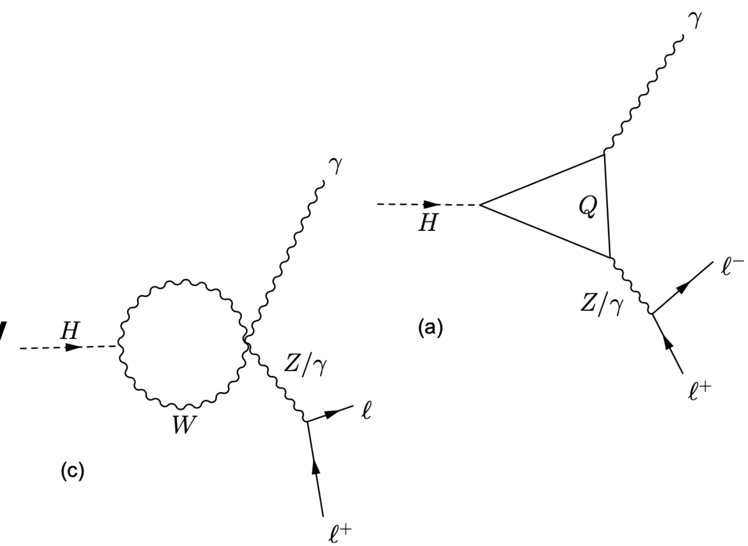
- $B(H \to ee) = (0.0 \pm 1.8) \times 10^{-4}$

95 % CLS limits for obs. (exp.):

- 3.6×10^{-4} (3.5×10^{-4})

H→Zγ decay search

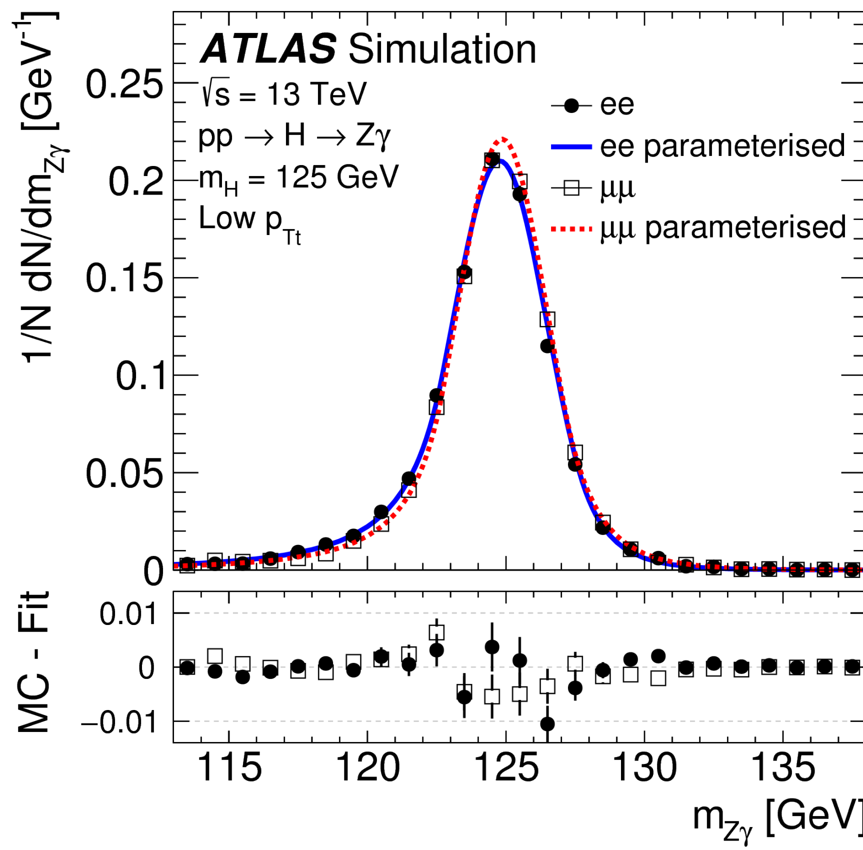
- more difficult than Higgs→γγ
  - (B[H→Zγ]×B[Z→ee/μμ]= ~10^{-4})
- **BUT**: Small background → great sensitivity



Sensitive to new physics through the loop diagrams (may contain new charged particles)

Focus only on **Z→ee/μμ** decays as they have good invariant mass resolution and background rejections

BUT: less signal than H->γγ



arXiv:1708.00212

H→Zγ decay search: Analysis strategy

Event selection → Categorisation → Signal

Event selection

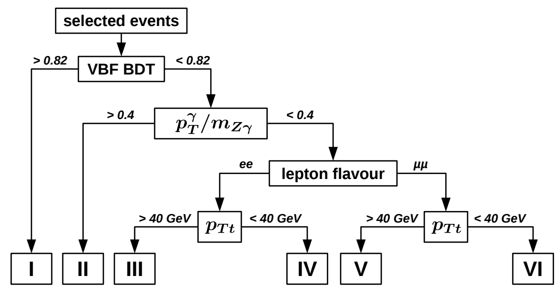
2 leptons, pT > 10 GeV
+ 1 photon, pT > 10 GeV

$|m_{ll} - m_Z| < 10$ GeV

$115 < m_{ll\gamma} < 170$ GeV

Categorisation

MVA VBF-like category + 5 cut-based categories

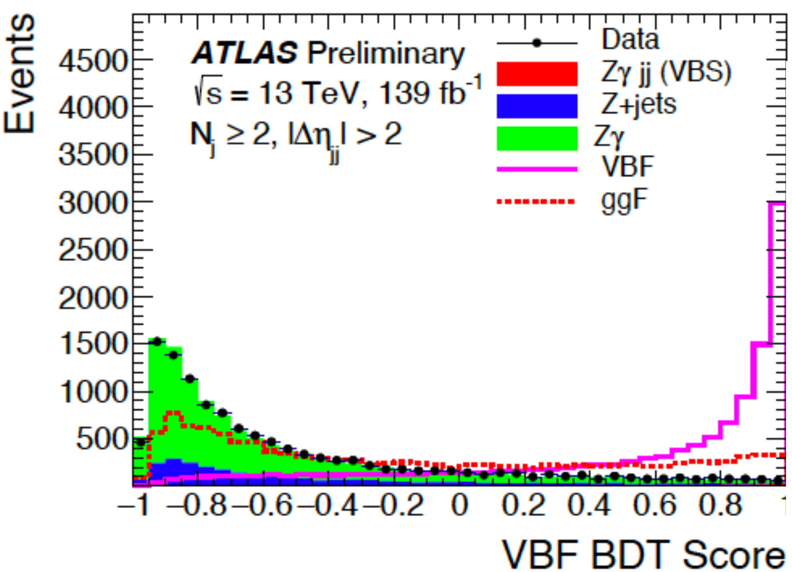


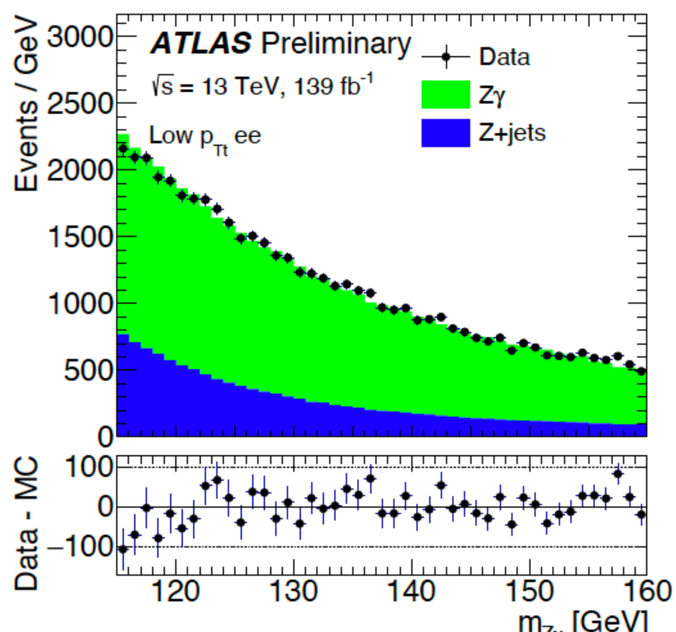
Signal

VBF, ggH, VH, ttH processes in each category sharing the same fixed DSCB model

Background

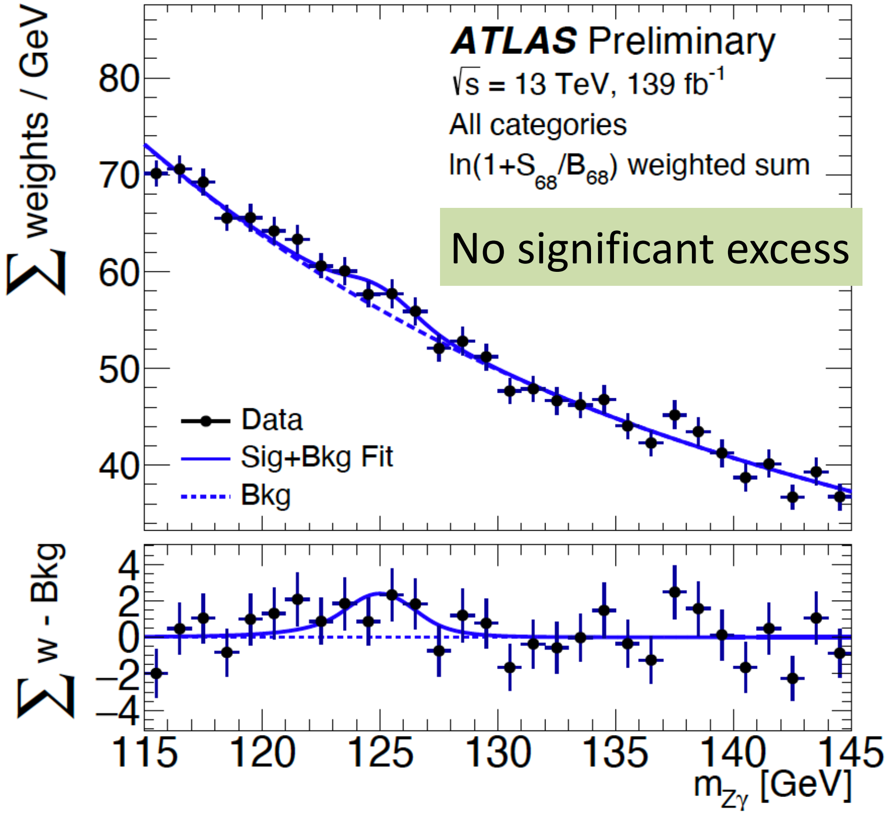
Zγ + Z+jets: parametric models and fit ranges selected to maximise the expected significance





significance improves by >40% vs the inclusive case

H→Zγ decay search: Results



NEW

For m_H = 125.09 GeV:

Best fit signal strength

$$\mu = 2.0^{+1.0}_{-0.9} = 2.0^{+0.9}_{-0.9}(stat.)^{+0.4}_{-0.3}(syst.)\ \text{(obs.)}$$

$$\mu = 1.0^{+0.9}_{-0.9} = 1.0^{+0.8}_{-0.8}(stat.)^{+0.3}_{-0.3}(syst.)\ \text{(exp.)}$$

Limits on μ at 95% CL:

Obs.: μ < 3.6

Exp: μ < 1.7 (2.6) assuming no (SM) H→Zγ

The total uncertainty is dominated by the **statistical component** (43%) of data, with a large contribution from the spurious signal systematic uncertainties (15%)

BR(H→Zγ) < 0.55% at 95% CL

σ∗BR < 305 fb at 95% CL

Summary

Rare or forbidden Higgs boson decays are presented

- $H \to Z\gamma$
- $H \to ee$
- $H \to \mu\mu$
- $H \to l\tau$
- $H \to e\mu$

Sensitive to the physics beyond Standard Model

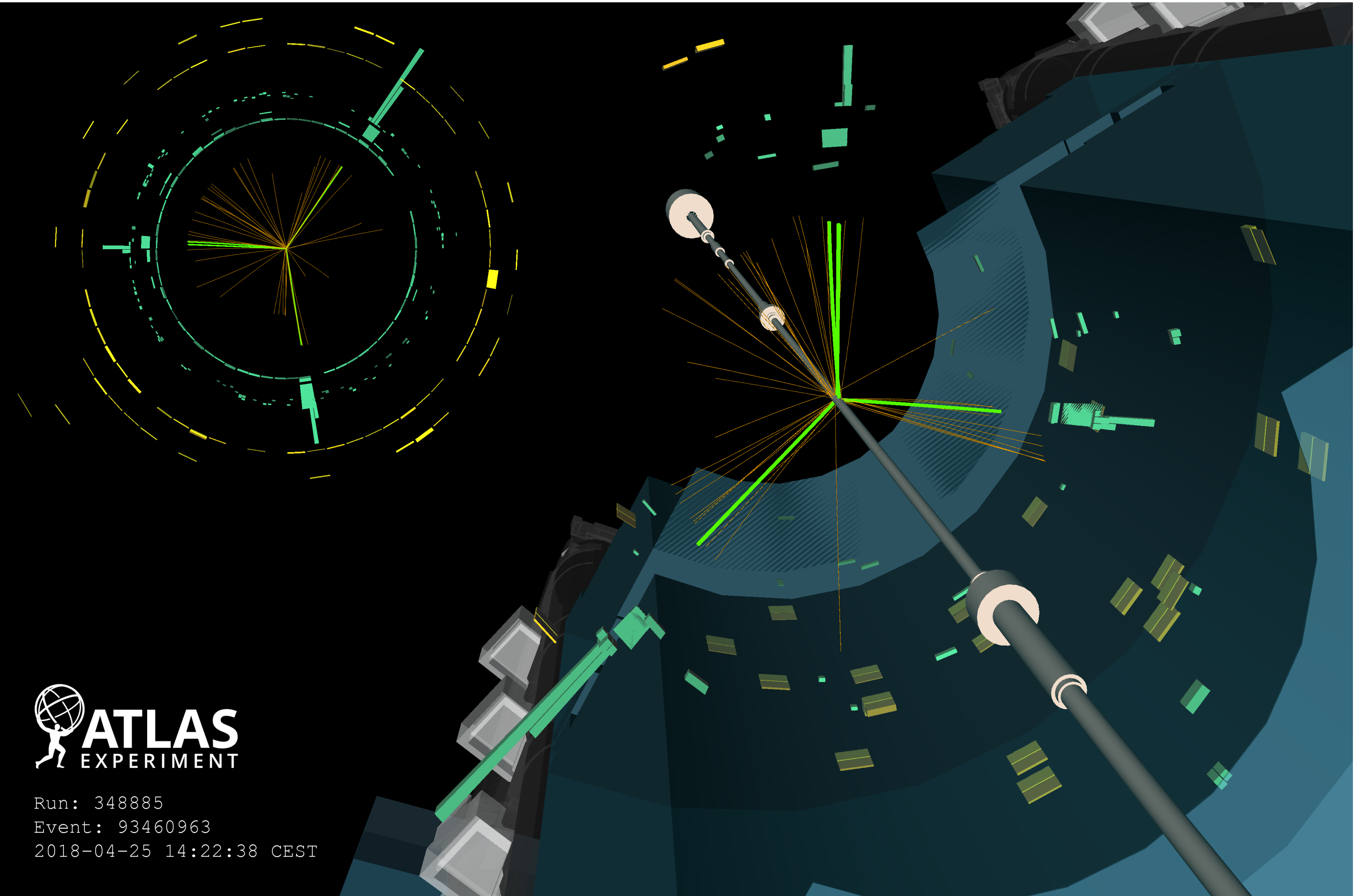
- No significant excess seen

Most of the analyses are still statistically limited

+ CP property constraints of the top Yukawa coupling with ttH+tH process and $H \to \gamma\gamma$ decays

Looking forward to Run3

Backup Slides



Lepton-flavour-violation with H→eτ/H→μτ

Analysis strategy

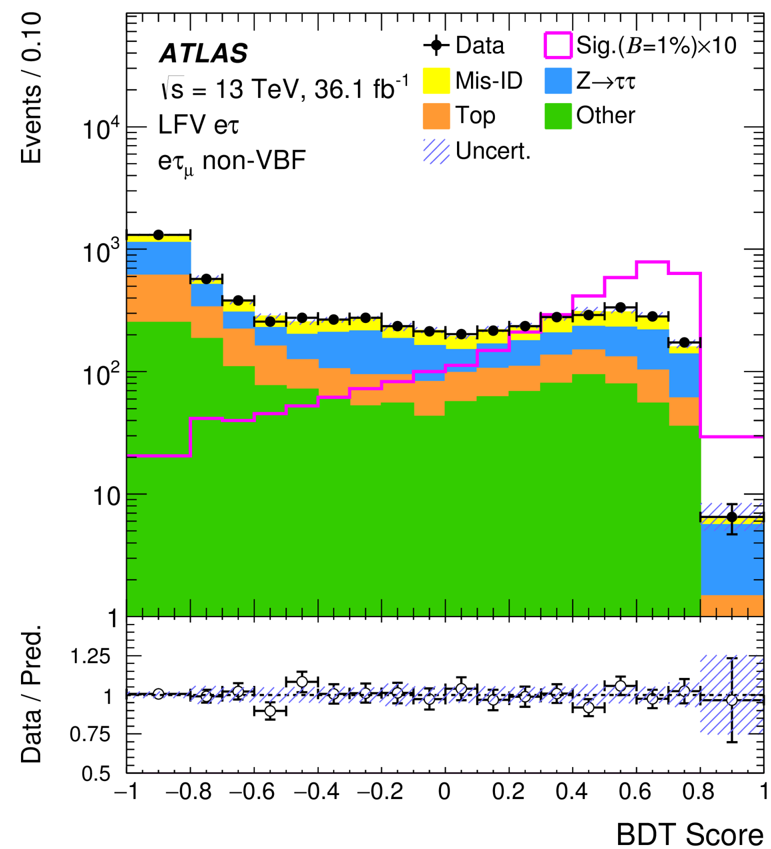
-Using MC and data-driven background to estimate SM bkg (SM H→ττ is background)

-2015+2016 dataset (**36 fb^{-1}**)

-Two independent channels:

- H→eτ or H→μτ considering both tau decay to leptons (τ_l) and with hadrons (τ_h)

- **MVA** performed to enhance the signal/bkg separation: BDT output used to perform a shape analysis of the data



- Analysis categories:
  - -VBF category (VBFH): n_{jets} >=2, high m_{jj}
  - -Non-VBF category (dominated by ggH)

- Exploited the jet kinematics, the leptons momentum disparity and the mass reconstruction

-Two Control Regions defined for the τ_{lep} sub-channel to constrain top and Zττ bkg

- Limits set on BR H→eτ and BR H→μτ separately

H→ee and H→eμ decay searches

Analysis strategy

- Data driven analysis; MC only used for signal shape fit and spurious signal fit in H→ee
- Event categorisation: 7 (8) categories for ee (eμ)
- The signal appears as a peak on top of a smooth background in the mll spectrum

- Signal parameterised as Crystal Ball + Gaussian for both decay channels
- Background parameterised as (Voigtian + $\exp[am_{ll}]/m_{ll}^3$) for ee, Bernstein polynomial for eμ
- Systematics accounted for as nuisance parameters in final fit
- Limits calculated from fit using CL_S method